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OPAQUE MINERALS OF STONY METEORITES

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Minerographic studies of opaque minerals, including nickel-iron, nickel-free iron, native copper, iocite, and ilmenite, in chondrites and achondrites, are discussed, with photomicrographs of grain distribution of the minerals in the groundmass and tabular data on chemical composition. In chemical composition and structure, the nickel-iron is analogous to that in iron meteorites; the nickel-free iron has been formed by troilite substitution; the ilmenite is similar to the terrestrial variety. Author

Stony meteorites are polymineral aggregates consisting mainly of minerals of the silicate class; opaque (ore) minerals are also present as secondary minerals and in the form of impurities. Today, 37 minerals and their varieties are known in stony meteorites, and almost a third of these are of the opaque type.

For the purpose of minerographic studies of opaque minerals, the author used both groups of the class of stony meteorites, i.e., chondrites and achondrites, as well as their variants.

As a result of our studies, we established the presence of nine minerals in stony meteorites, belonging to the classes of native elements, sulfides, and oxides.

All these minerals may be divided according to origin into three groups.

* Numbers in the margin indicate pagination in the original foreign text.

1. Nickel-Iron

Nickel-iron is the most widely distributed of all opaque minerals in stony meteorites. In the chondrites studied by the author, its content ranged from 7 to 12 wt.%. According to Daly, its mean content in chondrites is 10.58%.

The nickel-iron content in achondrites is low and sometimes it is entirely absent. For example, no nickel-iron at all was found in the Andronishkis achondrite. The mean content of nickel-iron in achondrites, according to data by Daly, is 1.57 wt.%.

In stony meteorites, as in iron meteorites, the nickel-iron consists of two mineral varieties, taenite and kamacite, which, as is generally known, differ from each other in their nickel content and show no continuous transition between them.

The kamacite of stony meteorites contains 5.5 - 6% nickel, while taenite has 25 - 30%. These two mineral varieties are easily differentiated in polished sections by their behavior on etching with 6% nitric acid or, preferably, with "nital" (a 6% solution of nitric acid in alcohol). On etching from several seconds to minutes, taenite remains unchanged while kamacite, under the microscope, appears grayish or coated with a film. In addition, taenite and kamacite are usually revealed on polishing the sections, as a result of their different hardness forming a microrelief.

Nickel-iron is identified under the microscope in reflected light according to its highly characteristic diagnostic indices. It is a mineral of white color. Index of reflection $R \cong 56\%$. Hardness 5 - 6; isotropic. Action of HCl and HNO_3 positive; the mineral foams and is blackened by $HgCl_2$. /79

According to form of segregation, the nickel-iron of stony meteorites can be classified into several characteristic types:

1) Xenomorphic formation;

2) Chondrules;

3) Emulsion structures (droplet grains);

4) Veinlets;

5) Dust grains.

1. Xenomorphic formations, compressed between grains of olivine, pyroxene, and other silicates. The sizes of such segregations are largest of all other forms of segregations of opaque minerals of stony meteorites, and range from hundredths of a millimeter to 0.6 mm. These segregations are often found in concretions with troilite (Fig.1), and sometimes also with chromite, and are encountered both in altered and unaltered chondrites, as well as in achondrites (Fig.2). As an example, let us consider a description of xenomorphic segregations in several varieties of stony meteorites, according to groups.

In unaltered chondrites, nickel-iron is observed both in the form of chondrules and in the form of xenomorphic segregations compressed between grains of silicates.

In the investigated Saratov chondrites, nickel-iron predominates in the form of xenomorphic segregations both in the body of the meteorite between the silicate chondrules and in the chondrules themselves. Often in the silicate chondrules the nickel-iron, in the form of small irregular grains intergrown with troilite, forms spongy structures located in the marginal portion of the chondrule, while in others it is more or less uniformly disseminated. In general, the quantitative content of nickel-iron in silicate chondrules is highly variable, ranging from tenths of a percent to several percent. Silicate chondrules containing almost no nickel-iron are also encountered.

In the Kain-saz chondrite, xenomorphic segregations of native iron are

infrequently found and gradually pass into spherical formations. In the crystalline chondrites, nickel-iron in its basic substance is found in the form of xenomorphic asymmetrical segregations. The size of such segregations ranges from several microns to tenths of a millimeter. Occasionally, the segregations reach 1 - 2 mm in size.

In the meteorites of Kunashak, Vengerovo, Holbrook and other crystalline chondrites, the author found various forms and structures of nickel-iron. Nickel-iron is observed in the form of irregular asymmetrical segregations, between grains of silicates in the body of the meteorite and often forms a component of silicate chondrules. In addition, grains of nickel-iron and troilite sometimes accumulate in a fringe around silicate chondrules.

Among the structural features of the nickel-iron of crystalline and nonmetamorphic chondrites, the presence of Neumann lines should be noted. These were detected under the microscope at high magnifications in the Sevryuk and Pervomaisk-Poselok meteorites (Fig.3). The author formerly took them for Widmanstätten patterns (Bibl.13), but, as proved by Professor F.Heide, they actually were plugs of kamacite composition.

Almost always on etching, plessitic fields mantled by taenite are revealed in segregations of nickel-iron (Fig.4). Regions consisting completely of plessite, which are fine-grained concretions of taenite and kamacite grains, are also encountered.

The following structures were brought out by etching in the plessitic /82 fields of the investigated stony meteorite (using A.N.Zavaritskiy's classification of plessite structures):

a) Perthitic plessite was found in the Holbrook meteorite. It consists of fine subparallel veinlets of taenite intersecting the kamacite. In some places

/80

Fig.1 Xenomorphic Segregations of Nickel-Iron (White) and Troilite (Light Gray) in the Silicate Groundmass of the Okhansk Meteorite
Reflected light; × 90

Fig.2 Segregations of Troilite (Light Gray) and Nickel-Iron (White) in the Silicate Groundmass of the Vavilovka Meteorite
Reflected light; × 90

Fig.3 System of Intersecting Neumann Lines;
Sevryuk Meteorite
Reflected light in oil immersion; × 1500

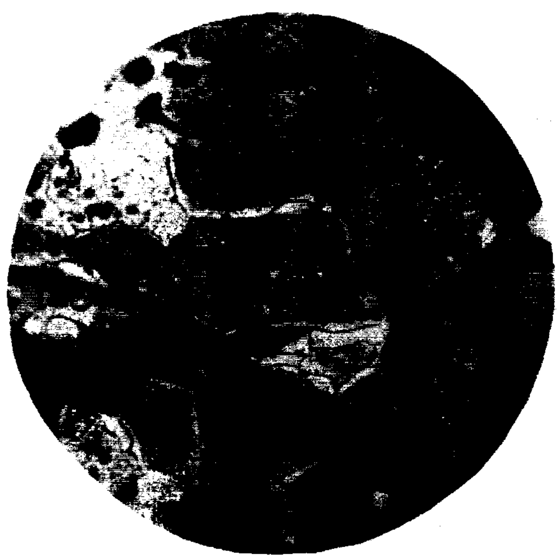

Fig.4 Plessite (Gray), Mantled by Taenite (White),
Brought Out on Etching
Gray spots with smooth surfaces: troilite;
Black: non-ore minerals. Kunashak meteorite
Reflected light; × 80

the veinlets are slightly sinuous. This texture recalls the perthitic structure of feldspars. The size of these perthitic formations is in the range of several microns (Fig.5).

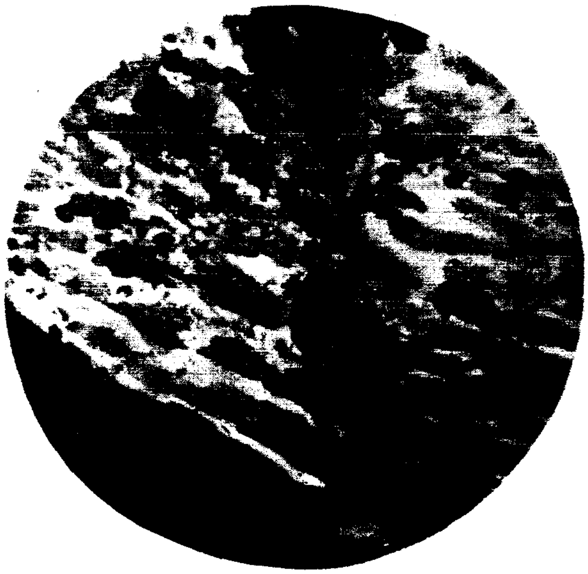

Fig.5 Plessite of Perthitic Structure Brought Out by Etching
White: grains of taenite in the kamacite groundmass (gray).
Holbrook's meteorite. Reflected light; × 600

b) Plessite with a structure strongly resembling a graphic texture, found in the Saratov and Holbrook meteorites, characterized by the appearance, in the kamacite groundmass, of taenite in sinuous and graphic forms (Fig.6).

c) Felsitoid (dense) plessite, usually of cryptocrystalline structure.

In altered and unaltered chondrites and in achondrites, kamacite and taenite are met as concretions of grains hundredths of a millimeter in size.

The etching of kamacite by nital sometimes brings out a granulitic structure with grain size down to a micron (Fig.7).

2. <u>Chondrules of opaque minerals</u>. In unaltered chondrites, the silicate chondrules are associated with a considerable number of chondrules consisting of opaque minerals, mainly nickel-iron and troilite.

In the black Kain-saz chondrite, almost the entire mass of nickel-iron and troilite consists of chondrules of various size, which in places have partially lost their original faces. Ore chondrules are met both in the silicate /83

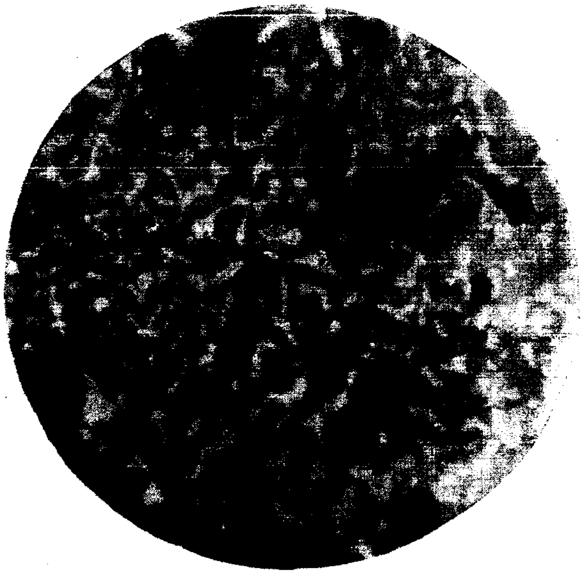

Fig.6 Plessite of Graphic Texture Brought Out by Etching
White: grains of taenite in the kamacite groundmass (gray).
Holbrook's meteorite. Reflected light; × 600

Fig.7 Granulitic Texture of Kamacite
Meteorite. Reflected light in oil immersion; × 1500

chondrules themselves and in the interstitial spaces. Their size ranges from several microns to 0.5 mm. According to mineralogical composition, polymineral chondrules predominate. Most often these consist of two minerals, nickel-iron and troilite. The nickel-iron and troilites in ore chondrules form aggregates of granular structure. The iron usually predominates. Such chondrules are most widespread, as already stated, in the Kain-saz chondrite and less often in the Saratov meteorite. Chondrules consisting of three, four, and even five minerals are relatively infrequent; they are found, for instance, in the Saratov /84 meteorite, whose silicate groundmass contains ore chondrules consisting of grains of nickel-iron, troilite, chromite, silicates, and native copper (Fig.8).

Fig.8 Chondrule Consisting of Nickel-Iron (White), Troilite (Light Gray), Chromite (Gray) and Silicates (Dark Gray) Saratov meteorite. Reflected light; × 200

Monomineral chondrules are comparatively rare and consist either of nickel-iron or of troilite, and in isolated instances of chromite. Their size is far smaller than that of the polymineral chondrules. Monomineral chondrules are

most often present in the form of inclusions in the glassy interstitial mass filling the space between spikes or between porphyritic segregations of silicate chondrules.

On structural etching with nital, kamacite fields (usually at the center) are brought out in a chondrule, showing a narrow taenite shell along the edges. Sometimes the granular structure is visible even without etching.

It should be noted that ore chondrules are occasionally also found in achondrites. They were encountered in the Vavilovka meteorite, where they were several microns in size, and consisted of troilite and nickel-iron; they were also present in the Staroye Pes'yanoye achondrite.

The following is a short description of the opaque chondrules in various meteorites.

Saratov. Nickel-iron is found both in spherical or ellipsoidal shapes, and in the form of asymmetric grains. A gradual transition is observed between the chondrules and the asymmetric grains of nickel-iron. Some iron chondrules have a granular structure, and the nickel-iron in them is intergrown with troilite. One of the observed ore chondrules, 0.3 mm in diameter, of polygonal-granular structure, contains up to 50% troilite, up to 40% nickel-iron, and about 10% non-ore minerals. It also has two grains of chromite and one grain of native copper, 0.01 mm in diameter (Fig.8).

Nital etching of the iron chondrules on the periphery brings out a taenite shell having a width hundredths or thousandths of a millimeter, mantling a field of felsitoid plessite.

Migei. Very rarely, the silicate part of the meteorite contains nickel- /85 iron in the form of chondrules of spherical or ellipsoidal shape, hundredths of a millimeter in size. Several chondrules have what appears like eroded edges,

i.e., a corrosive structure of substitution of the iron in the chondrules by another mineral, possibly by iron silicates (Fig.9). On etching the chondrules with nital, a taenite shell appears in the peripheral portion, while the inner portion of the chondrules consists of kamacite (Fig.10).

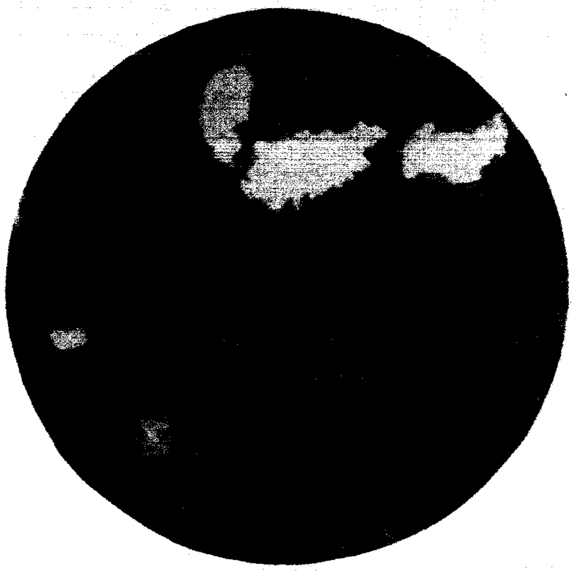

Fig.9 Chondrule of Native Iron (White)
Along the periphery, structure similar to the corrosive structure of substitution by secondary minerals (light-gray). Migei meteorite. Reflected light; × 600

Kain-saz. All the nickel-iron and troilite in this meteorite occurs in the form of chondrules, most of which are spherical; some of the chondrules have lost their original form and appear amorphous (Fig.11). The size of the chondrules ranges from several microns to 0.35 mm, and several of them are smaller than one micron. Chondrules of 0.03 - 0.01 mm in size are predominant in the cross section. Opaque chondrules are observed both in the groundmass (between the silicate chondrules) and within the silicate chondrules themselves; in the latter case, their size is of the order of hundredths and thousandths of a millimeter. An area of about 0.05 mm^2 was counted in one silicate chondrule,

Fig.10 Chondrule of Native Iron with Etchant-Revealed Taenite Shell Outside (White) and Plessite Inside (Gray) Migei meteorite. Reflected light; × 600

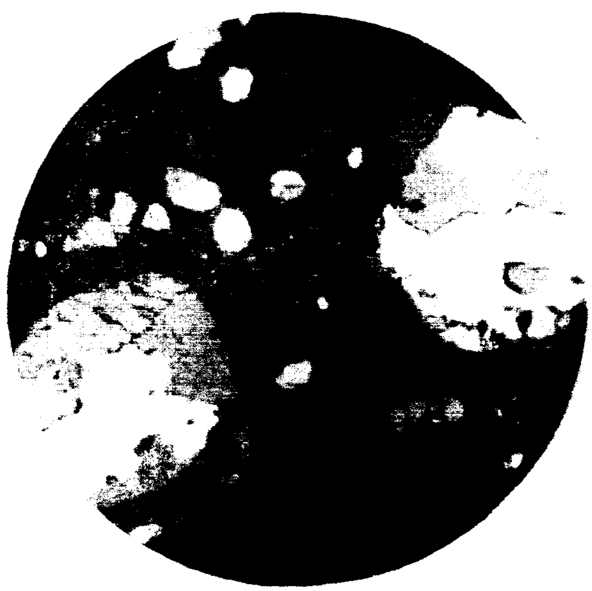

Fig.11 Chondrules Consisting of Native Iron (White) and Troilite (Gray)
The black area is the silicate groundmass. Kain-saz meteorite. Reflected light; × 400

giving a total number of 250 opaque chondrules 1 to 10 μ in size. Chondrules of nickel-iron alone or of troilite alone are also found. The chondrules most often consist of two minerals, nickel-iron and troilite, forming concretions of granular structure. In some chondrules consisting of nickel-iron, troilite is present in a thin shell several microns in thickness, surrounding the chondrule. Silicate chondrules of spicular structure are also found with small troilite chondrules several microns in size included between the columns and the glassy mass. Droplike inclusions of nickel-iron in the troilite chondrules were not encountered.

All these chondrules of troilite and nickel-iron, found in unaltered and /87 partially recrystallized chondrites, were in all probability formed simultaneously with the silicate chondrules during the formation of the meteorite. The unaltered state of the chondrites in which they are found is evidence of their contemperaneous origin.

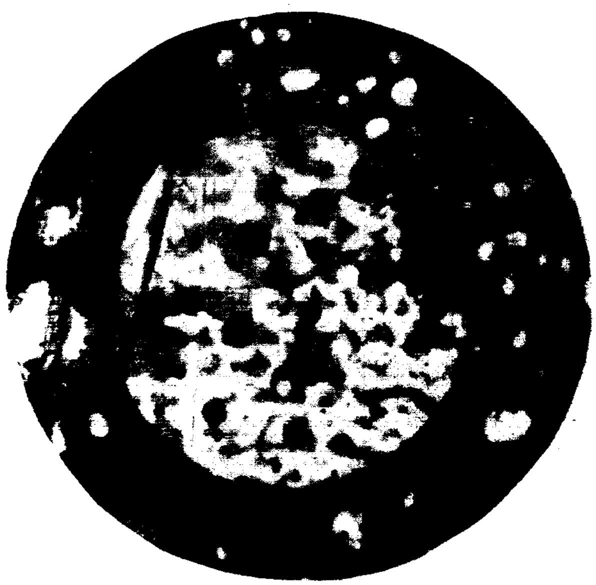

Fig.12 Mosaic Structure of Concretion of Troilite (Gray) with Nickel-Iron (White) in Segregations of Droplike Form (Spheres)
Black streak in the Pervomaisk-Poselok meteorite.
Reflected light in oil immersion; × 1500

The polysomatic ore chondrules found in the unaltered chondrites always have a granular structure, i.e., the troilite observed in the nickel-iron has the form of irregular allotriomorphic grains, as evident in the Kain-saz and Saratov meteorites.

3. Emulsion structures of troilite and nickel-iron. These are found in altered chondrites, mainly in their black varieties and in the black veinlets, as well as in some regions of the internal zone of the fused crust. A characteristic feature of the emulsion structure is the droplike form (globules) of the troilite and nickel-iron. In the black varieties and black streaks of meteorites, one or several round (droplike) inclusions of nickel-iron are usually observed in the small troilite globules hundredths of a millimeter in size. The troilite that includes the droplike forms of nickel-iron is not always of rounded shape, and sometimes irregular grains are observed.

Such ore formations of droplike form are found in the black varieties and black streaks of the Kunashak, Sevryuk and Pervomaisk-Poselok chondrites, and in the black Novyy Urey achondrite, of which a short description is presented below.

Sevryuk. Troilite segregations of spherical shape, measuring hundredths and thousandths of a millimeter, are often observed especially in the black varieties of the meteorite; in some places they have a slightly elongated form. Some troilite chondrites contain inclusions of extremely minute droplike grains of nickel-iron.

Vengerovo. Grains of troilite of spherical shape, with inclusions of small droplets of nickel-iron, are found in some places in the black streaks and in the internal zone of the fused crust. /88

Pervomaisk-Poselok. The gray variety of the meteorite contains a small

region hundredths of a square millimeter in area, of vitreous or cryptocrystalline structure. In this silicate mass, small globules consisting of nickel-iron and troilite are observed in large numbers. The internal structure of the globules is fine-grained (Fig.12); troilite with droplike inclusions of iron is also encountered (Fig.13).

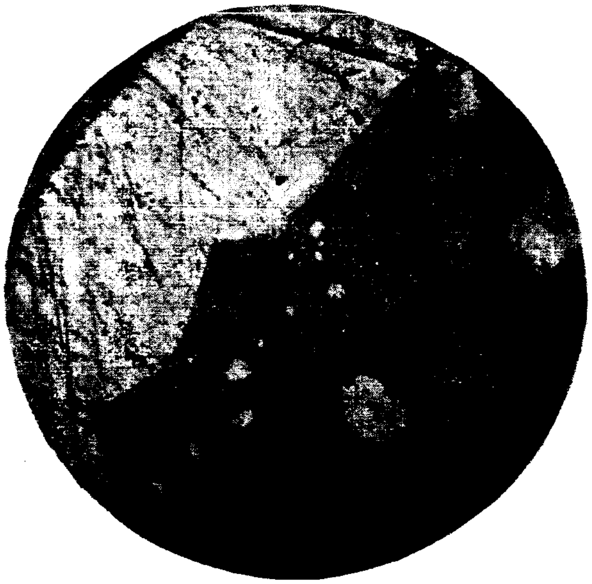

Fig.13 Radiate Growth of Troilite (Gray) with Droplike Inclusions of Nickel-Iron (White); Silicates (Black) Black variety of Pervomaisk-Poselok meteorite. Reflected light; × 600

Kunashak. Round or droplike formations of nickel-iron, included in troilite globules or in troilite inclusions not having a spherical form, are found in the black variety of the meteorite and in the black streaks. In the latter case, there is a gradual transition from the droplike forms of nickel-iron to irregular asymmetrical angular grains. Conversely, the troilite globules more often contain one (or less frequently two) droplike inclusions of nickel-iron. Etching with 6% nitric acid showed three grains with a mantle of taenite in one of the inclusions of nickel-iron surrounded by troilite (Fig.14). No inclusions

of troilite were encountered in the droplike formations of nickel-iron.

In the internal zone of the fused crust, the veinlets of troilite are accompanied by its round forms with droplike inclusions of nickel-iron. In most cases, etching with nital reveals a taenite shell on the periphery of the globules, having a thickness of several microns with kamacite or plessite in the center.

The same structural patterns of nickel-iron and troilite were obtained artificially on remelting the gray variety of the Kunashak, Pervomaisk- /89 Poselok, Saratov, and other meteorites at 1300° C under exclusion of air. As a

Fig.14 Structure of Nickel-Iron, Resembling Widmanstätten Patterns Revealed by Etching
The surrounding black fringe: etched troilite. Dark gray: silicate. Kunashak meteorite.
Reflected light; × 150

result of the experiment, globules and – in places – isometrically melted grains of troilite, with droplike inclusions of nickel-iron (Fig.15) in no respect different from the globules found in the black varieties of the meteorites, were formed in the remelted silicate groundmass of the meteorite.

Structural etching of the artificially obtained ore globules revealed a very fine fringe of taenite on their periphery, while the internal portion, apparently of kamacitic or fine-plessitic composition, darkened.

In the internal zone of the fused crust of stony meteorites, the ore globules were no doubt formed during passage of the meteor through the earth's atmosphere, which might also be true of the black streaks.

4. Fine veinlets. These are usually 1 - 2 μ or less in width, and sometimes up to several tens of microns in length. Occasionally, the veinlets are straight and occasionally sinuous lines. Intersecting in the plane of the polished section, the veinlets often form a net. The veinlets frequently follow the lines of the junction and fissures of the grains of the non-ore minerals and chromite. Almost always a veinlet consists of nickel-iron and troilite and has a granular concretionary structure.

On study of the fused crust of the Kunashak, Vengerovo, and Pervomaisk-Poselok meteorites, it was noted that the second zone of fused crust, consisting of veinlets, droplets and dustlike grains mainly composed of troilite and iron, passes into the black streaks of the meteorite without any changes in structure. This means that the black streaks and the black varieties of the Kunashak, Vengerovo, Pervomaisk-Poselok, and Sevryuk meteorites are analogous in structure to the second zone of the fused crust. It follows that their formation was likewise due to remelting of the meteorite substance as a result of heating.

The veinlets found in the carbonaceous achondrite of Novyy Urey, of a /90 width ranging from less than a micron to 0.025 mm, are of specific interest. The fine veinlets gradually change into a series of discrete dust specks of droplike shape, linearly oriented (Fig.16). The broad veinlets are always mantled with iron dust, to a greater or lesser degree. With respect to the

features of the Novyy Urey chondrite we should mention that the author found no mineral troilite in the veinlets of nickel-iron.

On etching the nickel-iron in the veinlets, a plessitic structure is revealed, i.e., sparse grains of taenite appear among the kamacite groundmass.

Fig.15 Troilite Globules (Light Gray) with Droplike Inclusions of Nickel-Iron (White) in the Silicate Groundmass of the Kunashak Meteorite after Heating to 1300° C
Reflected light; × 600

5. Dustlike grains of nickel-iron. These are found almost always together with troilite grains. The average size of such grains is 1 - 2 μ. The form of the grains is isometric and in places slightly elongated. These small granules ordinarily form irregular regions several millimeters in diameter. Such dustlike accumulations of nickel-iron, and also of troilite, are highly characteristic of the black varieties of metamorphic chondrites and of the black streaks. In the Novyy Urey achondrite, the fine dust of nickel-iron is segregated around the veinlets, forming a fringe hundredths of a millimeter in width. At high magnifications, one sees that this dust consists of extremely small solidified

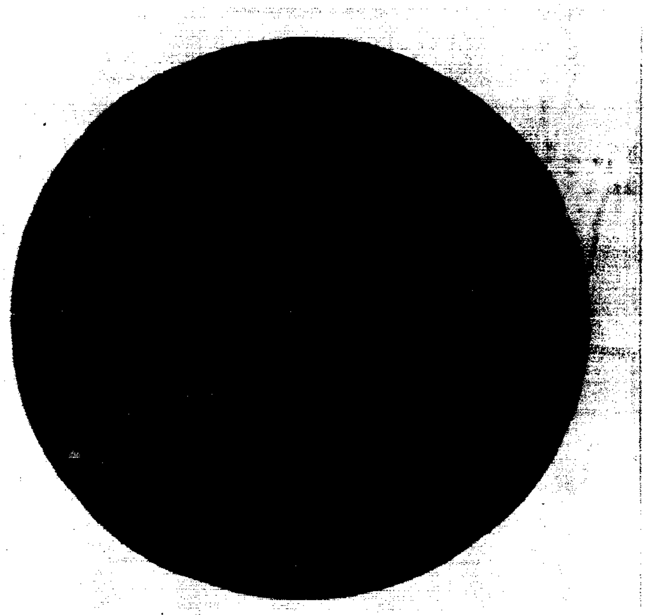

Fig.16 Linearly Oriented Droplike Grains of Nickel-Iron (White) in Silicate Groundmass of the Novyy Urey Meteorite
Reflected light in oil immersion; × 1500

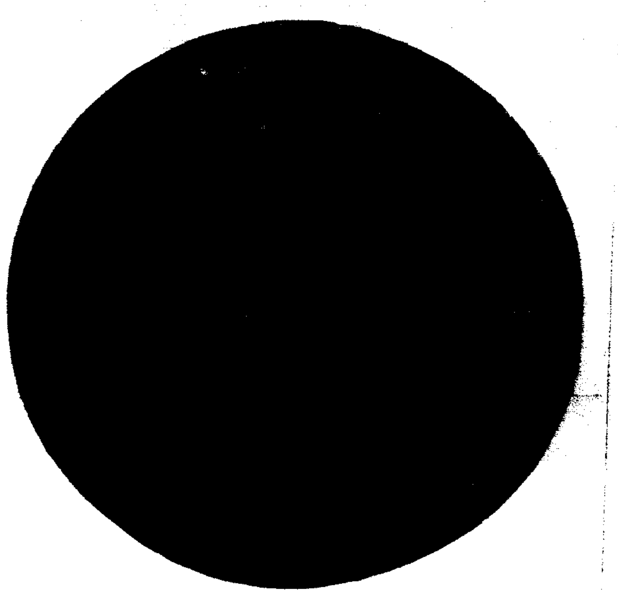

Fig.17 Dustlike Grains of Nickel-Iron (White) in Silicate Groundmass (Black) of Novyy Urey Meteorite
Reflected light in oil immersion; × 1500

droplets of iron (Fig.17).

X-ray diffraction studies on nickel-iron in the Saratov, Pervomaisk-Poselok and Okhansk meteorites and in the fused crust of the Kunashak meteorite (Tables 1 - 3), made by V.D.Kolomenskiy under the supervision of Professor V.I. Mikheyev, gave the following mean values for the sides of the elementary cells (a) of kamacite and taenite in kX*.

TABLE 1

SPECTRAL ANALYSIS OF NICKEL-IRON OF CHONDRITES (INDIVIDUAL GRAINS)

Chondrites	Elements				
	Ni	Co	Cr	Ge	Cr
Vengerovo	10.4	0.5	0.01 0.03	0,01 0,03	traces
Okhansk	7.3	0.5	0.01 0.03	0,01 0,03	»

TABLE 2

SPECTRAL ANALYSIS OF MAGNETIC FRACTION OF ACHONDRITES

Achondrites	Elements						
	Ni	Co	Ti	Mn	Al	Cu	Cr
Yurtuk	0.1	0.01	1	0.3	0.1	0,04	0.1
Novyy Urey . .	0.03	traces	traces	0.1	0.1	0,01	0.1

TABLE 3

CHEMICAL COMPOSITION OF MAGNETIC FRACTION OF ACHONDRITES

Meteorite	Fe, Metallic	MnO	CaO	MgO	Ni	Cu	Co	SiO_2
Sevryuk	44.18	—	—	—	6.01	0.40	0.20	—
Kunashak	57.80	0.12	0.73	9.00	9.72	0.53	0.35	15.48

1. In the nickel-iron of the Saratov meteorite, the following values /92
for "a" were established: for kamacites, a = 2.866 kX and for taenite, a =

* 1000 x = 1 kX = 1.00202 Å.

= 3.579 kX. Taenite is present as an insignificant admixture.

2. The nickel-iron of the Pervomaisk-Poselok meteorite also consists of kamacite with a = 2.864 kX and taenite with a = 3.585 kX, but the taenite is present in somewhat greater quantity than in the Saratov meteorite.

3. X-ray studies of a sample of nickel-iron from the Okhansk meteorite showed the presence only of the mineral kamacite, determined from a = 2.860 kX.

4. The nickel-iron of the internal zone of the fused crust of the Kunashak meteorite is kamacite with a = 2.864 kX.

In converting the elements to terms of minerals, we excluded the oxides SiO_2, MgO, CaO, and MnO as belonging to the minerals of the silicate class which was present in the sample in the form of a mechanical admixture, and of copper which, as we shall see below, forms an independent mineral in close association with nickel-iron. According to our computations, the chemical composition of the nickel-iron in the meteorite studies was as follows (Table 4).

TABLE 4

CHEMICAL COMPOSITION OF NICKEL-IRON (KAMACITE AND TAENITE) IN CHONDRITES

Meteorite	Elements		
	Fe	Ni	Co
Sevryuk . . .	87.67	11.93	0.40
Kunashak . . .	85.17	14.32	0.51

2. Nickel-Free Iron /93

Native iron, not containing nickel, was first found by Lacroix in the hypersthene meteorite of Tatauin, which fell in Tunis in 1931. The negligible quantity of metallic iron (0.79%) and the hypersthene itself contained no nickel.

Later, the finding of nickel-free native iron was confirmed by Professor P.N.Chirvinskiy's study of the Padvarnink achondrite (Bibl.5).

A study of the altered Sevryuk chondrite by the present author revealed the presence of native iron of secondary origin, not containing nickel. This iron had been formed from the troilite. In this meteorite, the native iron in both the black and gray variety forms finely granular and sometimes graphic intergrowths with the troilite. Several segregations of native iron were partially converted into iocite, starting from their edges.

Fig.18 Substitution of Troilite (Gray) by Nickel-Free Iron (White)
Sevryuk meteorite. Reflected light in oil immersion; × 1500

Microchemical testing of native iron for nickel, conducted by the present author with dimethylglyoxime, yielded negative results. Repetition of these microchemical reactions by A.P.Nasedkin and V.N.Meshkanova likewise showed the absence of nickel from the iron and troilite. In a diagnostic etching by HCl and HNO_3, the iron rapidly blackens without revealing any texture. Somewhat

similar substitution structures of troilite by iron were observed in the Nikol's-kaya and Vengerovo chondrites (Fig.18).

3. Native Copper

Grains of native copper were found by the author in the Vengerovo meteorite (Bibl.9). These grains are of elongated shape and are almost always associated with angular grains of troilite in nickel-iron (Fig.19). In further studies, /94 native copper was found in the unaltered chondrites of Saratov and Kain-saz.

The Saratov meteorite contains copper in the same form as the Vengerovo meteorite. In this meteorite, native copper in grains was found in a polymineral

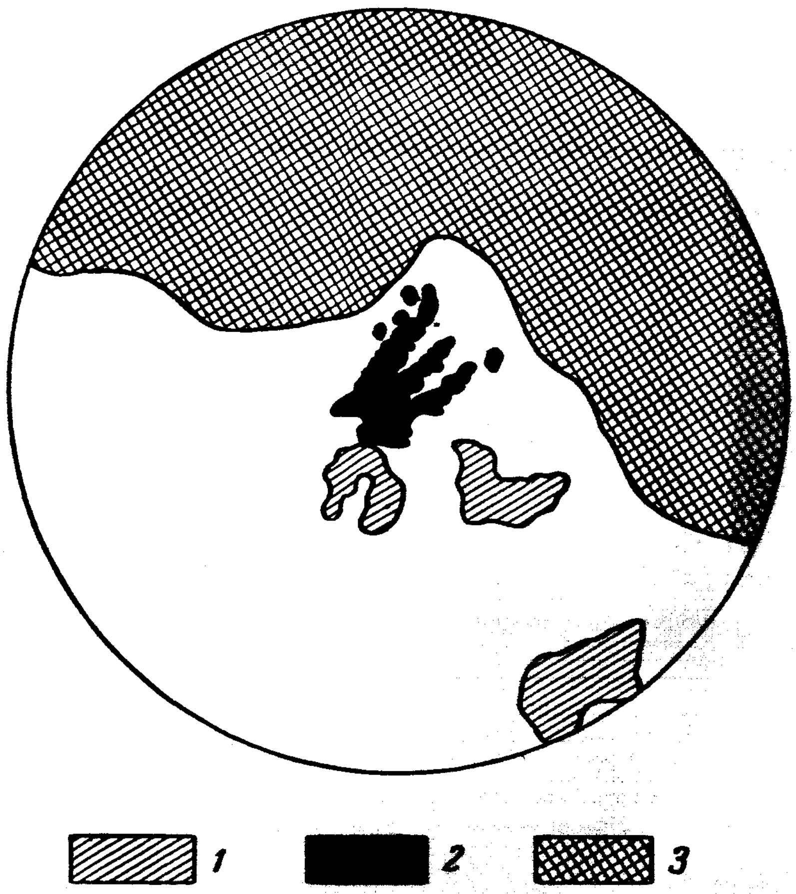

Fig.19 Inclusions of Native Copper (2) and Nickel-Iron (White)
1 - Troilite; 3 - Silicates. Vengerovo meteorite;
reflected light in oil immersion; × 1500

ore chondrule.

A polished section of the Kain-saz meteorite showed two grains of native copper, included in the silicate part of the meteorite; one grain was 0.03 × × 0.001 mm in size and the other, 0.02 × 0.01 mm.

As in the case of the Vengerovo and Saratov meteorites, the copper in the Nikol'skaya meteorite occurs in association with angular grains of troilite and nickel-iron. In regions where troilite "fragments" were absent from the nickel-iron, no native copper was found.

In polished sections, the copper is determined by the following signs: The color on freshly prepared surfaces is copper-red but changes to intense red within a short time. The index of reflection is higher than for iron. High luster. Low hardness, lower than that of nickel-iron. When the stage is raised, the line of light shifts from the copper to the iron. Diagnostic /95
etching with 1:1 HNO_3: positive; 5% $HgCl_2$ and 20% $FeCl_3$: positive; native copper starts blackening rapidly; KOH: positive.

4. Troilite

The shape of the troilite inclusions in stony meteorites resembles that of nickel-iron.

1. Relatively large inclusions (0.05 - 0.5 mm) of irregular angular shape are most frequent in chondrites and also in certain achondrites. They may possibly be syngenetic with the irregular inclusions of nickel-iron and chromite (see below on the latter).

2. As already noted, in unaltered chondrites, and also in certain regions of altered chondrites, troilitic chondrules are rather prevalent. Often the troilite in the troilitic chondrules is intergrown with nickel-iron; moreover,

there are also many chondrules that consist only of troilite. The size of the chondrules ranges from tenths of a micron to 0.15 mm.

Fig.20 Native Iron (White) in Concretions with Troilite (Light Gray)
Black dots: native copper; black outside: silicates.
Vengerovo meteorite. Reflected light; × 600

Emulsion structures of troilite are encountered in the black varieties, the black streaks, and in some portions of the inner zone of the fused crust of stony meteorites. A characteristic feature of such structures is the presence of troilitic globules with droplike inclusions of nickel-iron (cf. description of nickel-iron). There are also other forms that are characteristic of troilite.

3. Inclusions of troilite in the form of isometric lamellae 2 - 5 μ in size are sometimes present in considerable numbers in coarse segregations of nickel-iron. In some grains of nickel-iron, the content may reach 1 - 2 vol.%.

4. In certain iron grains of the chondrites, "fragments" of troilite are observed. The shape of such fragments is irregular and slightly elongated; /96 other regions have a texture close to pegmatitic (Fig.20). The size of these

grains is not over several microns. The mantling iron often is intergrown with large segregations of troilite.

Usually, the native copper in chondrites associates with such fragments of troilite, for example in the unaltered Saratov chondrite and in the altered Vengerovo and Okhansk chondrites.

Fig.21 Fine Veinlets of Troilite (White) Pierced by Silicates (Black) and Grains of Chromite (Dark Gray) Sevryuk meteorite. Reflected light in oil immersion; × 1500

Moreover, isolated grains of troilite, mantled by iron of irregular thickness, were found in the Vengerovo meteorite in the spaces between the chondrules. By analogy with terrestrial minerals, such fringes of iron around the troilite grains can be compared with the fringes that appear when one mineral is substituted by another.

For the black varieties, the black streaks, and the internal zone of the fused crust of stony meteorites, the following forms of troilite are most characteristic:

a) veinlets ranging in width from tenths of a micron to several microns, and tens of microns in length (Fig.21);

b) dustlike grains of size up to several microns;

c) troilite globules;

d) spongy formations with small silicate inclusions (Fig.22);

e) relatively large grains of troilite of irregular shape, included in the silicate portion of the groundmass of the meteorite.

It should be noted that the forms of segregation of troilites are analogous to those of segregation of nickel-iron, except for the third form; therefore, a more detailed description is omitted.

Troilite is identified by the following signs: color, cream; index of reflection, R ≅ 39%; hardness, medium; strongly anisotropic; foams on etching with HCl and HNO_3, giving off H_2S. $HgCl_2$ and $FeCl_3$: negative. Nonmagnetic.

The results of a spectral analysis of the monomineral fraction of troilite of the Kunashak meteorite are given in Table 5.

TABLE 5 /97

SPECTRAL ANALYSIS OF TROILITE FROM STONY METEORITE OF KUNASHAK
(Analysis by A.A.Yavnel')

Fe	++	Cu	0.01
Ni	0.05	Si	1
Co	0.01	Al	0.01
Cr	0.5	Ge	0.001
Mg	0.5	V	-
Mn	0.1	Ti	-

++ Very strong lines.

X-ray studies of the troilite of the Holbrook meteorite gave the following results: a = 5.970 kX; c = 11.67 kX.

Fig.22 Cellular Structure of Troilite (Light Gray)
and Nickel-Iron (White)
Dark gray: silicates. Sevryuk meteorite.
Reflected light; × 400

5. Iocite

Iocite is a very rare mineral. On earth is has been found in the ferruginous lavas of Vesuvius in the form of black crystals of cubic syngony. The mineral has an NaCl type crystal lattice.

As to the possibility of finding iocite in meteorites, we have only the statement by P.N.Chirvinskiy who reported the presence of iocite in the black variety of the Pervomaisk-Poselok chondrite (Bibl.6).

In a minerographic study of the gray variety of the Sevryuk meteorite, the present author found iocite as infrequent formations. On further study of this meteorite, iocite was discovered in considerable quantity also in the black variety of the meteorite, where its content reached 0.6 vol.%.

In both varieties of this meteorite, iocite is associated with troilite /98
and iron. In the gray variety of the meteorite in some regions, iocite forms a

thin shell (in the plane of the polished section, a fringe) several microns wide around the segregations of native iron, sometimes with ramifications of extremely fine veinlets of a thickness not over a micron. The native iron surrounded by iocite almost always has a granular structure, less often a graphic concretionary structure with troilite, and in some regions a graphic texture of substitution of iron by iocite. In that case grains, sometimes vermicular, of troilite are observed in the iocite mass. In the polished section No.48, the gray variety of the Sevryuk meteorite shows segregations of iocite which, in form, resemble single crystals with clearly demarcated faces, which are not observed in the minerals from which they were formed.

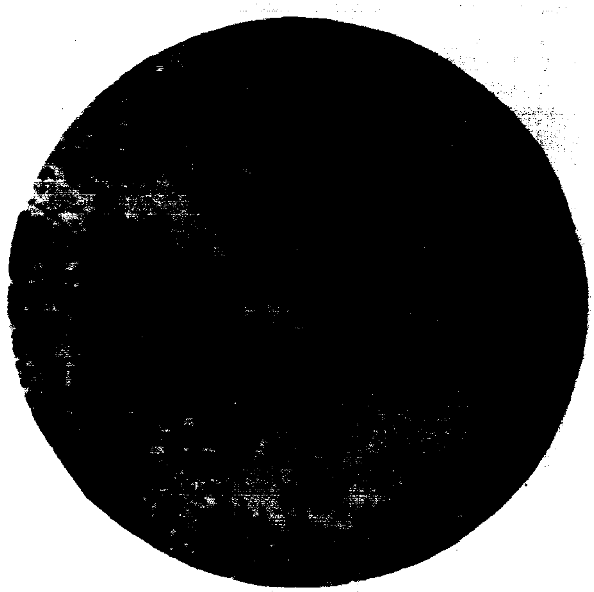

Fig.23 Corrosive Structure of Substitution of Native Iron (White) by Iocite (Gray)
Sevryuk meteorite. Reflected light; × 600

In the black variety of the Sevryuk meteorite, besides the above described formations, corrosive substitution structures are formed as a result of the replacement of nickel-iron by iocite. In some grains of nickel-iron, iocite forms individual zones starting from the edges, and sometimes almost two thirds of the

entire grain is transformed into iocite. Such formations have the characteristic corrosive substitution structure (Fig.23).

It should be noted that the black color of some varieties of stony meteorites is apparently due to the presence of finely divided iocite.

Iocite is identified in reflected light by the following signs: gray color, index of reflection $R \cong 16\%$, isotropic, absence of internal reflections. The diagnostic etching of $HgCl_2$ and $FeCl_3$ is negative. HCl is positive, and the mineral blackens. Under the action of HNO_3, foaming is observed. Wüstite, an artificially prepared ferrous oxide has similar diagnostic signs.

The formation of iocite is due to thermal metamorphism of the meteorite. A mineral with similar identifying features was found by the author in the fused crust of the Sikhota-alin iron meteorite. X-ray studies of iocite from the fused crust of the meteorite yielded a value of a = 4.284 kX as the mean value for its unit cell. A substance of the same composition as iocite, known under the name of wüstite, was prepared by the author in the laboratory. /99

Several bits of nickel-iron of the Sikhota-alin meteorite, from tenths of a millimeter to several millimeters in size, were taken for the experiment. A mixture of bits of this meteorite and magnetite powder was placed in an iron tube of 8 mm diameter and 23 mm length. Iron plugs were inserted on both ends of the tube and the contents were pressed under a pressure of 120 atm. The preparation was then placed in a muffle furnace at 1000°C for 29 hrs.

As a result of these experiments, iocite was formed along the edges of the nickel-iron fragments. It had a corrosive substitution structure of iron, similar to a graphic texture.

6. Ilmenite

In examinations of stony meteorites under reflected light, the mineral

ilmenite was first found by the author in the Vengerovo chondrite. Ilmenite here is observed in the silicate groundmass of the meteorite in concretion with chromite and nickel-iron. The index of reflection of ilmenite, which is higher than that of the chromite associated with it, attracted the author's attention. In four polished sections of the Vengerovo meteorite, with a total area of 925 mm^2, carefully examined at high magnification, only two grains of ilmenite were found in all. One of them was 0.15 × 0.07 mm in size and the other, 0.12 × × 0.08 mm.

Later, sparse grains of ilmenite, measuring hundredths of a millimeter, were observed in the stony Sevryuk meteorite in both the gray and black varieties. In the polished section No.54 prepared from the black variety of the Sevryuk meteorite, a grain of ilmenite 0.01 mm in size was found in the nickel-iron. Outwardly the grain is a single crystal with clearly defined faces.

It should be noted that, in the investigated chondrites, the ilmenite is a very rare mineral encountered only in the form of individual grains. For example, in five polished sections of the Kunashak meteorite, with a total area of 1546 mm^2, no ilmenite was discovered even at careful examination.

The largest quantity of ilmenite has been found in the feldspathic achondrite of Yurtuk. The total content is 0.4 vol.%. The ilmenite segregations are found here in concretions with troilite, chromite, and iron. The size of the grains varies considerably, from thousandths of a millimeter to 0.2 mm. In some grains a lamellar concretionary structure of ilmenite-chromite is visible.

In the polished section No.96 prepared from the Yurtuk achondrite, fine lamellae of ilmenite from 0.01 to 0.002 mm in width and 0.02 to 0.06 mm in length (Fig.24) were observed in a grain of chromium-spinellid 0.12 × 0.06 mm in size. This texture resembles the structures of titanomagnetites of the Ural

deposits, in which, however, magnetite instead of chromite is observed.

Grains of ilmenite with well-defined lamellar twinning are observed. In the polished section No.96 we found a grain of ilmenite 0.2 mm in size showing

Fig.24 Lamellar Structure of Concretion of Ilmenite (White) and Chromium-Spinellid (Light Gray) Dark gray: silicates. Yurtuk meteorite. Reflected light; × 600

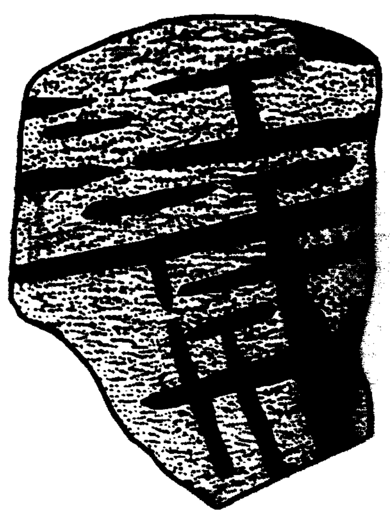

Fig.25 Twinned Structure of Ilmenite Yurtuk meteorite. Reflected light; crossed nicols; × 400

the intersection of two systems of twinned lamellae which formed a reticular structure (Fig.25).

In another feldspathic achondrite, that of Andronishkis, the amount of ilmenite found by the author was as much as 0.2 vol.%. In this meteorite, ilmenite is present in formations analogous to the ilmenite formations of the Yurtuk achondrite. /100

Ilmenite is identified in reflected light in polished sections from the following signs: color of the mineral, brownish-gray; reddish-brown tinge in oil; weak double reflection; strongly anisotropic. The index of reflection (verified with an Inostrantsev camera) is R ≅ 17 - 18%, somewhat higher than in the associated chromite. The hardness is high, not scratched by a steel needle. The powder is black. Diagnostic etching with the usual standard chemical reagents is negative. A characteristic sign for ilmenite is the presence of twinned structures.

A chemical analysis of the Yurtuk meteorite by N.N.Dulova revealed 0.36% TiO_2 and 0.39% Cr_2O_3. A chemical analysis of another eucrite of Chervonyy Kut by Sokolova showed 0.71% TiO_2. Consequently, in these feldspathic achondrites the Ti content is higher than the mean content of 0.25% TiO_2, obtained in comparison analyses of 19 eucrites and howardites by P.N.Chirvinskiy (Bibl.7).

7. Chromite /101

Chromite occurs rather widely in stony meteorites. It is found in every meteorite in some amount. Usually, its content in the investigated stony meteorites is 0.2 - 0.3 vol.% and reaches 0.5% only occasionally. In some meteorites, the chromite content does not exceed hundredths of a percent, for example in the Kain-saz chondrite, in which grains of chromite are very seldom observed.

Chromite is found in stony meteorites in the form of irregular grains, most often compressed between grains of silicates. The predominant occurrence in stony meteorites is in the form of inclusions of chromite 0.1 - 0.005 mm in size, similar in shape to the coarse segregations of nickel-iron on troilite observed in the gray varieties of the meteorite, in the groundmass, i.e., between the chondrules. Isometric and droplike formations resembling chondrules, several microns in size, are sometimes encountered. Such small segregations of chromite are sometimes observed within the silicate chondrules or mantling them in the form of chainlets.

In feldspathic achondrites, as already noted, a concretionary structure of chromite-ilmenite is observed in some chromite grains. In the black varieties, in the black veinlets, and in the inner zone of the fused crust of stony meteorites, grains of chromite are sometimes mantled by a thin shell of troilite and sometimes pierced by fine troilite streaks.

TABLE 6

SPECTRAL ANALYSIS OF CHROMITE FROM THE KUNASHAK METEORITE (ACCORDING TO A.A.YAVNEL')

Fe	10	Cu	Traces
Ni	0.05	Si	+
Co	0.01	Al	0.5
Cr	++	Ge	0.01
Mg	8-10	V	0.5
Mn	0.5	Ti	1.0

++ very sharp lines
+ sharp lines

Chromite is determined in reflected light from the following signs: Mineral of gray color. Reflecting power (verified by the Inostrantsev camera) same as that of terrestrial chromite, R ≅ 16%; isotropic. Hardness high; not scratched by steel needle. Internal reflections observed in oil immersion: from yellowish-

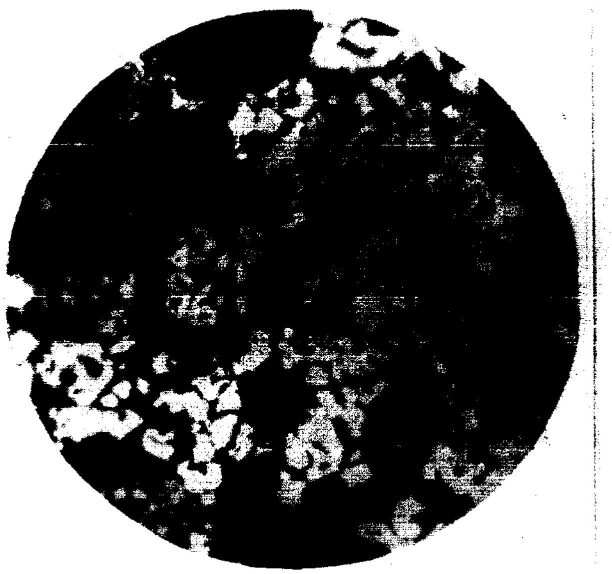

Fig.26 Grains of Oxymagnetite (White) in Silicate Portion (Black) of the Outer Zone of the Fused Crust of the Kunashak Meteorite
Reflected light in oil immersion; × 1500

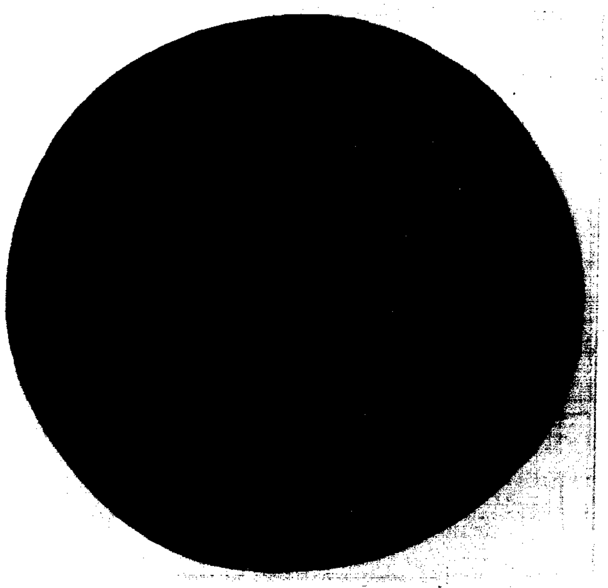

Fig.27 Grains of Oxymagnetite (?) (White) in Remelted Silicate Portions (Black) of the Sevryuk Meteorite
Gray: silicate. Reflected light; × 600

brown to reddish. Action of conventional chemical reagents: negative.

Table 6 summarizes the results of a spectral analysis of the monomineral chromite fraction, taken from the Kunashak meteorite.

7. Oxymagnetite

The fused crusts of the Kunashak, Vengerovo, Pervomaisk-Poselok, Saratov, and other stony meteorites showed very minute opaque grains 1 - 2 μ in size in varying quantities, ranging from a few percent up to 50 vol.% (Fig.26). The shape of these grains was isometric, in some cases octahedral. The grains were included in the glassy silicate groundmass.

Under the microscope, in reflected light, these minute grains are identified by the following signs: Mineral of gray color, with index of reflec- /103 tion $R \cong 15 - 16\%$, i.e., an index appreciably lower than that of magnetite; isotropic. No internal reflection observable. In oil immersion, the color of the mineral remains unchanged. The mineral is magnetic. Action of chemical reagents: negative.

In oil immersion preparations under the microscope in transmitted light, some grains have a dark-brown color under transillumination.

On the basis of the above diagnostic signs, we classified this mineral as magnomagnetite.

Subsequently, in investigations of the fused crusts of iron and stony meteorites, this mineral was subjected to an X-ray analysis by V.D.Kolomenskiy, under the supervision of Professor V.I.Mikheyev.

In the outer zone of the fused crust of the Sikhota-alin iron meteorite, this mineral was determined as a mineral of the spinel group, of the formula $(Fe^{II}_{1-x}Fe^{III}_{2/3x})Fe^{III}_2O_4$, where $x \neq 0.15$. Professor V.I.Mikheyev proposed that it be

classified as oxymagnetite.

Judging from the conditions of formation and the same diagnostic signs, this composition is probably an opaque mineral of the external zone of the fused crust of stony meteorites. Analogous grains of opaque mineral, formerly taken for magnetite (Fig.27), are found in the vitreous silicate portion of stony meteorites.

8. Conclusions

As a result of our study of stony meteorites, the following conclusions may be drawn.

1. Nickel-iron found in stony meteorites is in many respects, as to structure and chemical composition, analogous to the nickel-iron of iron meteorites. It consists of two mineral forms: kamacite and taenite. The presence of emulsion structures in the black portions, in the black streaks, and black meteorites, both chondrites and achondrites, is evidence that they have been heated to rather high temperatures.

2. Nickel-free iron found in the Sevryuk and Vengerovo chondrites is of secondary origin. Based on its structural features, the nickel-free iron may be considered as having been formed by substitution of troilite.

3. Native copper is found in both altered and unaltered chondrites. It is usually encountered in native iron in association with small grains of troilite in places with a skeletal substitution structure.

4. Iocite is found in the Sevryuk chondrite and in the fused crust of the Sikhota-alin iron meteorite; this mineral was formed at high temperatures.

5. Ilmenite found in meteorites is analogous to terrestrial ilmenite, both in diagnostic and structural features. As in the terrestrial titanomagnetites

(of the Urals), fine concretionary structures of ilmenite with chromite and oxymagnetite are observed here.

Similar to ilmenites of terrestrial origin, twinned ilmenites, forming reticular structures are encountered, pointing toward compressive processes. A higher ilmenite content (up to 0.5%) is observed in feldspathic achondrites. In chondrites, ilmenite is present in the form of isolated grains or is entirely absent.

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